Simulation Model of PVDF Piezoelectric Transformer for Medical Applications

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Abstract – **The current paper proposes a simulation model of piezoelectric transformer model that utilizes the Polyvinylidene Fluoride (PVDF) material. Its piezoelectric properties and medical applications are still being researched and minor information about such model is present. The available models for conventional transducer are compared and adaptation is proposed. The piezoelectric transformer model is described and its parameters are discussed. A PSpice simulation and laboratory experiment are accomplished. The results are compared and discussed.**

Keywords –**piezoelectric transformer, PVDF, transducer model, energy transfer**

I. INTRODUCTION

The piezoelectric transformers have numerous advantages like compact shape (low height) and high efficiency due to the native driver circuit soft switching [1]. They are used for high voltage step-up applications with capacitive load. Normally PZT material is used in multilayer transformer structures. The piezoelectric transformers transfer energy using mechanical acoustic wave that propagates to small distances up to few centimeters without significant energy loss. They also obtain low EMI and can be used for powering small sensitive to interference electronic devises or for charging small batteries from distance. These qualities could be meaningful for medicine for implantable devices such as pacemakers, implantable defibrillators, brain 'Pacemakers' for Alzheimer, cochlear implants etc. In some cases the battery life is few years on account of occupying most of the volume in the device housing. Miniaturization requires smaller battery that needs to be recharged and coils with electromagnetic waves are not always the solution because they can influence sensitive electronics or cause unwanted effects on human body. Piezoelectric transformer, working with acoustic waves within the safe regulations, can be the proper solution.

The acoustic wave propagation medium between the primary and secondary transducers in the medical piezoelectric transformer is the human tissue. The acoustic impedance of the human skin is *1.99 MRayl*, bones - *5.32 MRayl* [2] and of the ordinary transducer material which is lead-zirconate-titanate (PZT) - *39.71 MRayl*. The mismatching of impedances causes energy reflection that can be major problem especially for the energy receiving unit. Therefore polyvinylidene fluoride (PVDF) is used as it has acoustic impedance equal to *2.7 MRayl* (close to human tissue and water), develops high piezoelectric activity and is flexible and tough.

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The PVDF material is extruded into thin piezo film with typical thickness between *9* and *110* μm. Electrodes are made of silver ink [3] and piezo film elements are laminated with Mylar film [4]. All these materials are compatible with the human body and are not rejected normally.

This paper focuses on PVDF piezoelectric transformer that utilizes thickness mode vibrations. It can be considered as one or multiple transduces that transmit acoustic waves and one or multiple transduces that receive these waves. Therefore conventional piezoelectric transducer models can be used, employing electroacoustic analogous circuits for analysis of the electro-mechano-acoustics. Normally piezoelectric transformers are described using electromagnetic transformers [1] and Mason's transducer model [5]. Other option is the KLM model [6]. They are powerful tools for conventional piezoelectric transformers but they become difficult to adjust when different layers are present between the primary and secondary elements or when multiple transducer elements are used. On other hand transmission lines are useful for modelling multilayered structures where piezoelectric and non-piezoelectric layers are present. Such models are proposed by Redwood [7] and Leach [8].

This article presents a model of PVDF piezoelectric transformer that employs Leach's model because of the use of transmission lines for the mechanical analogous circuit and controlled source technique for connection between the mechanical and electrical parts. The model is implemented in the circuit simulator PSpice, which is a part from the OrCAD software tool suite [9], where driver circuit and secondary side electronics can be included to the model.

II. MODEL THEORY

The PVDF piezoelectric transformer consists of primary and secondary piezoelectric elements that will be considered as transducers. The primary side transducer performs electrical to mechanical conversation and the secondary side – mechanical to electrical.

Ultrasonic transducers operate at wide frequency range, therefore the high frequency approximation of the transducer model should be accurate enough for the whole operational range. This is hard to obtain for materials with low quality factor Q because the difference between the model and the exact solution became unacceptable. So the acoustic losses in the material must be taken into account and lossy transmission lines should be used. Some materials like the piezoelectric polymer film have frequency dependent dielectric parameters and Q factor so that the film capacitance and lossy transmission line resistive parameter varies. However the piezoelectric transformer operates at fixed sinusoidal frequency and the

PVDF lossy transmission line parameters and the piezo-film element capacitance can be accurately determined.

Leach's thickness-mode transducer model is used, because the acoustic wave propagates in direction of the film's thickness which is also the direction of the electric field (electrodes are printed on both sides of the film).

For the presented simulation model the following assumptions and simplifications are made: the piezoelectric transformer model operates only in one direction as the energy flows from primary to secondary side; the acoustic wave propagates only in one dimension; the amplitudes are small enough to work in linear regions of components.

The Leach's model consists of mechanical and electrical analogous circuits representing the electro-mechano-acoustic system.

A. Mechanical analogous circuit

The equations, describing the one-dimensional compressional acoustic wave of piezoelectric transducer, can be modified to the form of telegraphist's equations [8]. Therefore the mechanical behavior of the PVDF transducer is described with a mechanical analogous circuit which is represented by a lossy transmission line, given on Fig. 1. The lossy transmission line can be modeled with lumped segments, consisting of series inductance L' and resistance R' per unit length, and parallel capacitance C' and conductance G' per unit length [10].

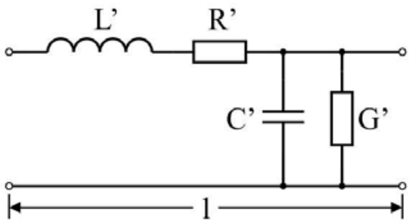

Fig. 1. Lossy transmission line

An impedance type analogy is chosen so that the mechanical force is represented by voltage and the particles velocity is represented by current. The inductance per unit length *L' [H/m]* and capacitance per unit length *C' [F/m]* are given by Eq. 1 and Eq. 2:

$$L' = \rho \cdot A \tag{1}$$

$$C' = \frac{1}{c^2 \cdot \rho \cdot A}, \tag{2}$$

where ρ is the density *[kg/m³]* and *c* is the speed of sound *[m/s]* in the PVDF material, and A is the cross sectional area *[m²]* of the acoustic beam.

The acoustic coefficient of attenuation α *[Np/m]* for frequency dependent materials like PVDF is given by Eq. 3:

$$\alpha \approx \frac{\omega \cdot \sqrt{L \cdot C}}{2 \cdot Q_M}, \tag{3}$$

where ω *[rad/s]* is the angular frequency and Q_M is the mechanical quality factor. The attenuation of the acoustic waves is represented by resistance per meter *R' [Ω/m]* which is given by Eq. 4:

$$R' = 2 \cdot \rho \cdot c \cdot A \cdot \alpha \tag{4}$$

The conductance per unit length *G [S/m]* is considered to be *0* and the transmission line length *l* is given in *[m]*.

B. Electrical analogous circuit

The electrical analogous circuit and the lossy transmission line of the primary side transducer are given on Fig. 2.

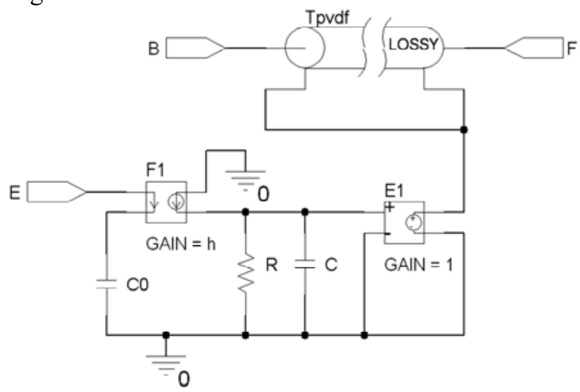

Fig. 2. Primary side transducer schematic

The transducer front and back sides are represented by ports 'F' and 'B' and the electrical port by 'E'.

The capacitance of the primary piezoelectric element is represented by capacitor C_0 and is given by Eq. 5:

$$C_0 = \frac{\varepsilon_S \cdot A}{d}, \tag{5}$$

where ε_S *[C²/N·m²]* is the dielectric permittivity at zero or constant strain, *A [m²]* is the surface area of the electrodes (normally same as cross sectional area of the acoustic beam) and *d [m]* is the distance between the electrodes (normally the same as the transmission line length *l*). The dielectric permittivity of PVDF material is determined from Eq. 6:

$$\varepsilon_S = \varepsilon_R \cdot \varepsilon_0, \tag{6}$$

where ε_0 *[C²/N·m²]* is the dielectric permittivity of vacuum and ε_R is the frequency dependent relative permittivity of PVDF material, found from Fig. 3.

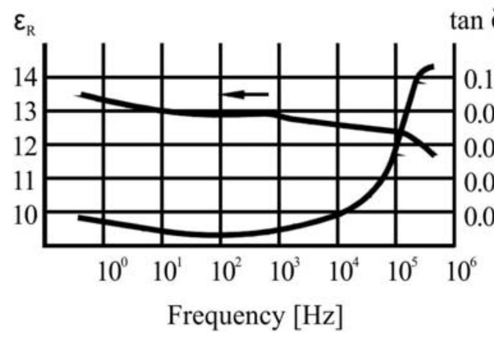

Fig. 3. Dependence of dielectric permittivity and dissipation factor of PVDF versus frequency [3]

The connection between the electrical and mechanical analogous circuits is accomplished with the current controlled current source *F1* with gain that is equal to the transmitting constant *h [N/C]* and is given by Eq. 7:

$$h = \frac{e_{33}}{\varepsilon_S}\,, \tag{7}$$

where e_{33} *[C/m²]* is the piezoelectric stress constant.

The resistor *R* and capacitor *C* integrates the current from *F1* and the unity gain voltage controlled voltage source *E1* isolates the integrator.

The electrical analogous circuit and the lossy transmission line of the secondary side transducer are given on Fig. 4.

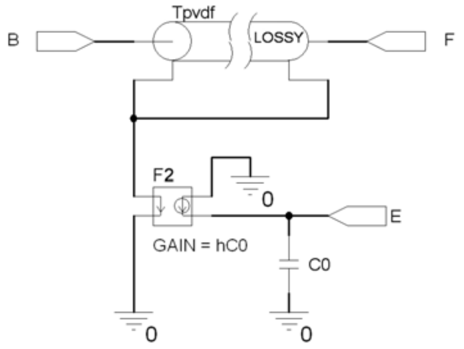

Fig. 4. Secondary side transducer schematic

The capacitance C_0 of secondary piezoelectric element is determined similarly from Eq. 5. The connection between the mechanical and the electrical analogous circuits is accomplished by current controllable current source *F2* with gain equal to the product of *h* and C_0.

III. Model Implementation

The proposed simulation model of PVDF piezoelectric transformer is implemented in PSpice (Fig. 5). The primary side transducer circuit is placed in hierarchal block *Primary Transducer* and the secondary side transducer circuit – in hierarchal block *Secondary Transducer*. The transducers' coating is represented by transmission lines *Tmyl* and the water medium – by *Twat*. The transducer backing that reflects the acoustic wave and is accomplished with aluminum plates [11][12], is represented by resistors *RAl*. The resistance is given in Eq 8:

$$R = Z_0 \cdot A\,, \tag{8}$$

where Z_0 is the acoustic impedance of aluminum.

The physical properties of the used materials in the PSpice simulation are summarized in Table 1.

Table 1. Physical properties of materials

Parameter	PVDF	Mylar	Water	Al
ρ [kg/m^3]	1780	1180	998.2 @ 25°C	2700
c [*m/s*]	2200	2540	1482.4 @ 25°C	6420
Q_M	13	30	-	-
ε_S [*pF/m*]	106-113	-	-	-
α [*Np/m*]	-	-	0.205 @ 500kHz	-
Z_0 [*Mrayl*]	2.7	3.0	1.48	17.33

The PVDF transducer has capacitive nature so that high *di/dt* causes very high initial currents. The combination with constant transmission mode when working as transformer causes failure of the thin electrodes and the connectors caused by the high local currents. As a result sine wave transducer excitation is used that also facilitates to determine the PVDF transmission line parameters. It is accomplished with sine voltage source *V1*.

The PVDF film transducer elements both for primary and secondary sides are FLDT1-028K piezoelectric film elements [4] with active film (electrode) area - 12 mm wide and 30 mm long. The film size is 28 μm having thickness mode resonance at frequency 39.28 MHz due to Eq. 9:

$$f_r = \frac{c}{2 \cdot d} \tag{9}$$

However the simulation model operational frequency is *500 kHz* because it is much easier to obtain in laboratory environment for experimental validation.

The 'Time Domain' PSpice simulation results are shown on Fig. 6 and simulation model parameters are given in Table 2.

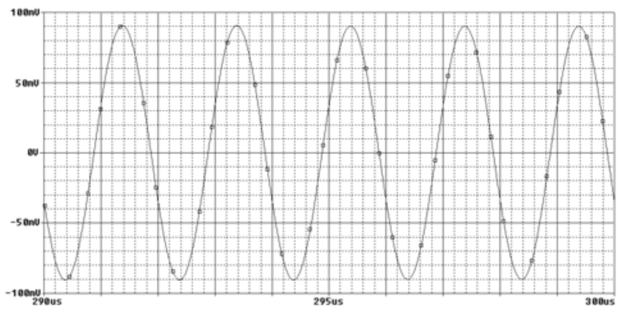

Fig. 6. Voltage over resistor *Rload* vs. time in PSpice

The piezoelectric transformer output voltage, developed over *1 kΩ* load resistor, has 'pure' sine wave shape with amplitude about 90 mV.

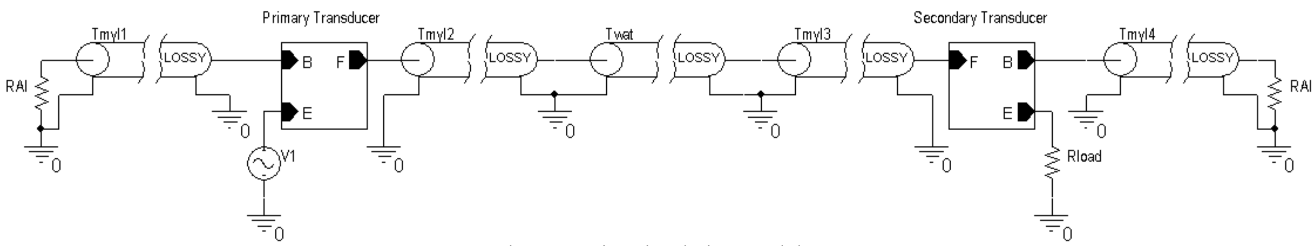

Fig. 5. PSpice simulation model

TABLE 2. SIMULATION MODEL PARAMETERS

Element	Parameters
Tpvdf	C = 322.4n, G = 0, L = 640.8m, LEN = 28u, R = 154.8k
C0	Value = 1.343n
F1	GAIN = 1.256e9
F2	GAIN = 1.687
E1	GAIN = 1
R	Value = 1k
C	Value = 1
V1	FREQ = 500kHz, VAMPL = 100V
Rload	Value = 1k
RAl	Value = 6.239k
Tmyl	C = 324n, G = 0, L = 486m, LEN = 88u, R = 50.9k
Twat	C = 1266n, G = 0, L = 359.3m, LEN = 15m, R = 6.6

IV. VALIDATION

To validate the PSpice model a physical experiment is accomplished. The experimental setup is given on Fig. 7

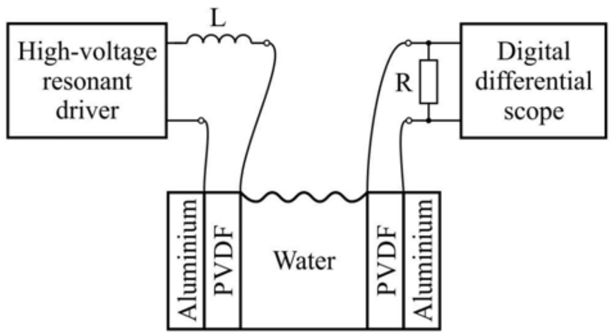

Fig. 7. Experimental setup

The two PVDF film elements (FLDT1-028K) are glued with epoxy onto vertical aluminum plates which are fixed in water environment on 15 mm distance. The primary transducer excitation is accomplished with high-voltage resonant driver and series inductor which together with the piezo-film capacitance creates LC resonant circuit, so that sine voltage with boosted amplitude is obtained.

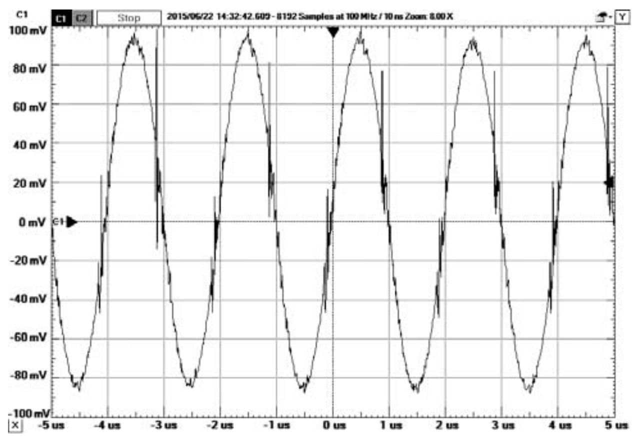

Fig. 8. Voltage over load resistor vs. time in experimental setup

The load is realized with carbon film resistor and the output voltage is digitalized and measured with battery powered digital differential scope 'Analog Discovery ™' of DIGILENT Inc. [13]. The experimental results are shown on Fig. 8. The piezoelectric transformer output voltage, developed over *1 kΩ* load resistor, has sine wave shape with moderate noise and amplitude about *90 mV* and *10 mV* positive offset, which is very similar to the simulation results.

V. CONCLUSION

The proposed PVDF piezoelectric transformer model in PSpice is a powerful tool for accurate simulation of the electrical energy transfer trough human tissue and other biological and non-biological media. The model can be used for evaluation of the potential and design of PVDF piezo-electric transformer for specific medical applications. The model is limited due to frequency variation and waveform but provides freedom for multi-material and multilayer designs.

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REFERENCES

[1] M. S. Rodgaard, T. Andersen, K. S. Meyer. *Design of Interleaved Interdigitated Electrode Multilayer Piezoelectric Transformer utilizing Longitudinal and Thickness Mode Vibrations*, IEEE International Conference on Power and Energy (PECon), December 2012

[2] H. Azhari. *Basics of Biomedical Ultrasound for Engineers*, April 2010, ISBN: 9780470465479.

[3] Measurement Specialties. *Piezo Film Sensors Technical Manual*, 25 March 2008, www.meas-spec.com.

[4] Measurement Specialties. *FDT Series Elements with Lead Attachment*, 05 December 2009, www.meas-spec.com.

[5] W. P. Mason. *Electromechanical Transducers and Wave Filters*, Princeton, 1948

[6] R. Krimholtz, D. A. Leedom, G. L. Matthaei. *New equivalent circuit for elementary piezoelectric transducers*, Electron. Lett., vol. 6, no. 13, pp. 398-399, June 1970

[7] M. Redwood. *Transient performance of a piezoelectric transducer*, J. Acoust. Soc. Am., vol. 33, no. 4, pp. 527-536, April 1961

[8] W. Marshall Leach. *Controlled-Source Analogous Circuits and SPICE Models for Piezoelectric Transducers*, IEEE Transaction on ultrasonics, ferroelectrics and frequency control, 1994, Vol. 41, No 1.

[9] http://www.orcad.com

[10] A. Puttmer, P. Hauptmann. *SPICE Model for Lossy Piezoceramic Transducers*, IEEE Transaction on ultrasonics, ferroelectrics and frequency control, 1997, Vol. 44, No 1.

[11] J. van Deventer. *Modeling an Ultrasonic Transducer with SPICE*, Proceedings of annual conference on CSEE, 2000.

[12] L. F. Brown. *Design Considerations for Piezoelectric Polymer Ultrasound Transducers*, IEEE Transaction on ultrasonics, ferroelectrics and frequency control, 2000, Vol. 47, No 6.

[13] http://www.digilent.inc